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Revolutionary Imaging: Air Force Contributions to Laser Guide Star Adaptive Optics

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The 178th meeting of the American Astronomical Society (AAS) in Seattle, Washington, in May 1991 provided the ideal setting for Robert Q. Fugate, technical director of the Air Force's Starfire Optical Range at Kirtland Air Force Base (Albuquerque, New Mexico), to make a dramatic announcement. His groundbreaking, classified laser guide star* work during the 1980s had been an unqualified success. Now for the first time, that information could be released to the public.

*A laser guide star is an artificial beacon created by a laser focused in the lower atmosphere. A wavefront sensor on the ground measures distortions in the return light (backscatter) caused by atmospheric turbulence.

When Bob Fugate walked up to the microphone at one o'clock to deliver his paper, he was a little nervous as he gazed out across the audience to find the room jam-packed. Nearly 400 people had showed up, with some standing two to three deep in the back and along the sidewalls.

Fugate did not disappoint his audience as he got to the heart of the matter right away. The first words out of his mouth were delivered in a confident and deliberate manner, announcing: "Ladies and gentlemen, I am here to tell you that laser guide star adaptive optics works!" To provide historical substance and scientific credibility to his opening statement, Fugate projected two images of the binary star *53 Ursa Major* on a large screen behind him. The uncompensated image shown on the left of the screen appeared as a blank in the heavens. But the image on the right side of the screen, compensated with laser guide star adaptive optics, dramatically revealed a clear image of *53 Ursa Major*, an improvement greater than a factor of 25 over conventional astronomical imaging *(Figure 1)*. Fugate explained that this photo "…was taken while the deformable mirror was continuously correcting atmospheric wavefront distortions." In scientific jargon, this was known as a "closed-loop" system. It consisted of three key components—a wavefront sensor, a high-speed processor, and a deformable mirror—that could keep up with the constant changes in atmospheric turbulence (occurring hundreds of times per second) and produce a high-resolution image.[1]

For a brief moment there was utter silence. The speechless scientists in the audience tried to grasp the significance of Fugate's startling announcement. Within seconds, a steady flow of noisy chatter broke out as they turned to one another and began muttering about the amazing image that they had just seen.[2]

Fugate's presentation that day created a big stir not only in the conference room, but very quickly in the astronomy community as a whole. Bill Thompson, a technical advisor at Phillips Laboratory at Kirtland Air Force Base who led the declassification effort, recalled it was "quite a day" as the astronomers were simply dumbstruck by the impact of the classified information, which was released all at once. "A lot of people in the audience," Thompson observed, "were stunned by the amount of work that had already been done by the Department of Defense…that was presented at the meeting." Wayne Van Citters, from the National Science Foundation, remembered the people listening to Fugate's presentation slowly leaning back in their chairs, mentally regrouping, and reacting with one telling word—Wow![3]

Fugate explained that the *53 Ursa Major* image was made on March 16, 1990, more than a year after his team had closed a laser guide star loop for the first time as part of the Generation I series of experiments conducted at the Air Force Weapons Laboratory at Kirtland. He also told the AAS group that the Air Force had sponsored laser guide star adaptive optics research since the summer of 1982—a shocking revelation to the academic astronomers in the audience—and described his first laser guide star experi-

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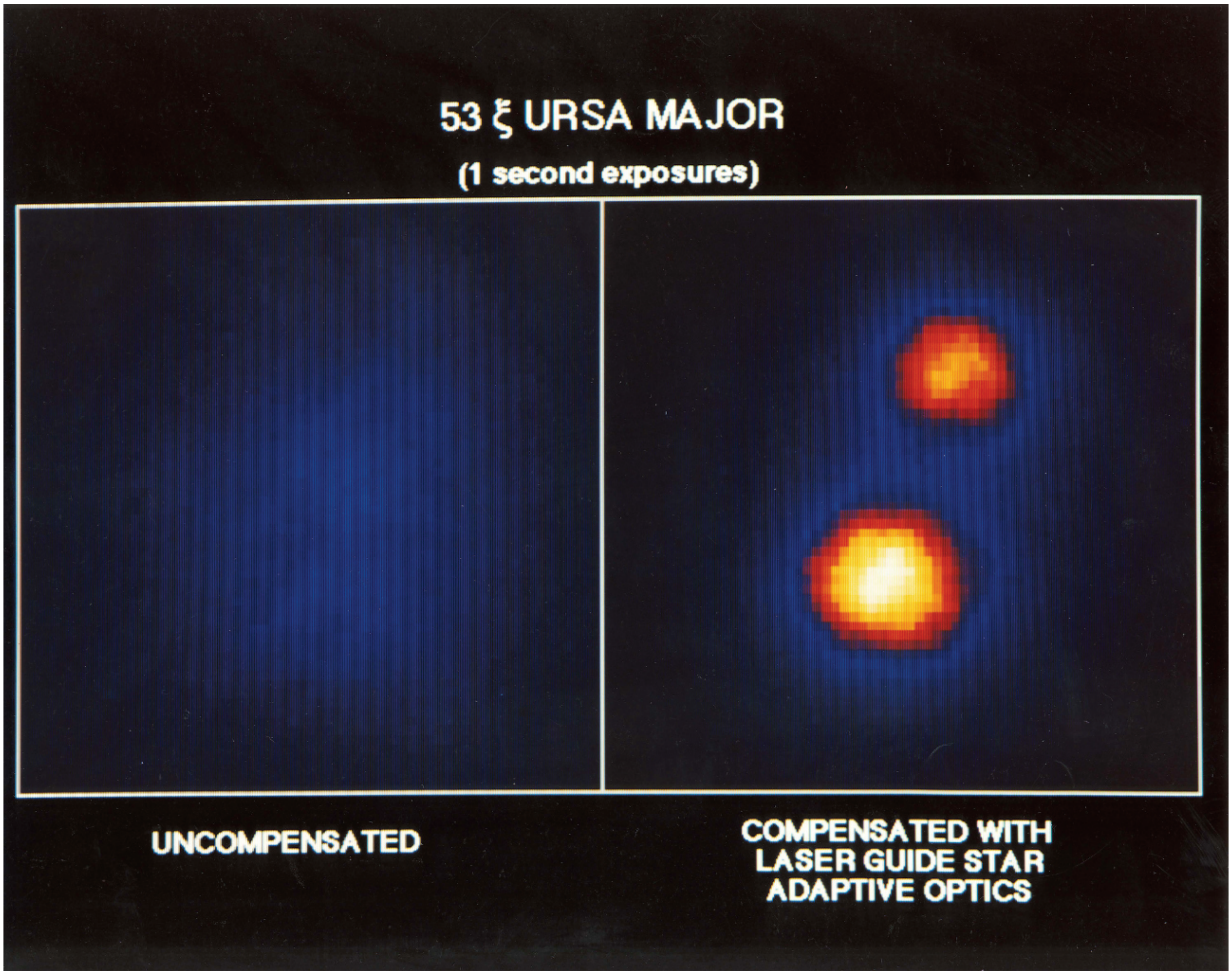

Figure 1. Bob Fugate's first image shown during his presentation at the American Astronomical Society Meeting in Seattle on May 27, 1991.

ment conducted in the fall of 1983. Fugate told the gathering, "Just to convince you that we didn't get one lucky picture," he showed a series of additional compensated images to reinforce the reliability of the laser guide star technique[4] *(Figure 2)*.

Why was there so much commotion over the release of Fugate's guide star work? He and his Air Force colleagues had done something revolutionary—they had begun to conquer the age-old problem of atmospheric turbulence causing distortion in light waves. Distorted light waves produced blurred rather than razor-sharp images of objects in space *(Figure 3)*. Fugate's laser guide star technique was a critical first step in the adaptive optics process that would eventually "compensate" distorted light by removing the effects of atmospheric turbulence, thus enabling high-resolution images. That was important to the military, which wanted to be able to take clear images of satellites, missiles, reentry vehicles, and space debris as part of its space situational awareness mission, and

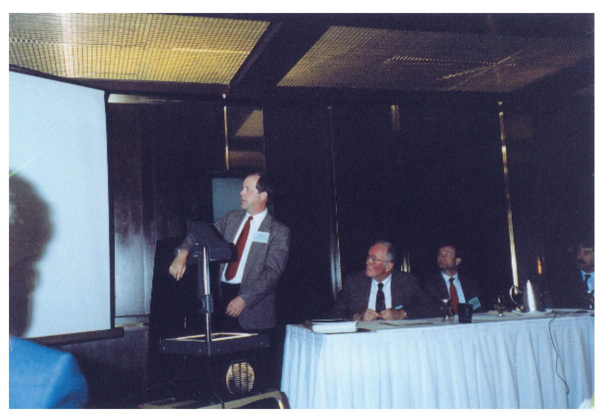

Figure 2. The day after his formal presentation to the American Astronomical Society, Bob Fugate briefed the press on his revolutionary laser guide star findings, while Charles H. Townes (center) and MIT/Lincoln Lab's Charles A. Primmerman (next to Townes) look on.

equally important to astronomers, who wanted ways to improve the image quality of planets, stars, galaxies, and other celestial bodies.[5]

Above all, adaptive optics needed to address atmospheric turbulence caused by temperature fluctuations in the atmosphere. Gases that make up the atmosphere are constantly moving at different speeds, much like the surface water in the oceans. Some sections of the ocean can be perfectly calm with a mirror-like surface, while other regions of the same ocean experience violent, churning surf, and tidal wave conditions. In the atmosphere, similar conditions exist. Temperature changes at various altitudes in the atmosphere result in changes to the air density refractive index, which causes one section of a light wavefront to bend differently and move ahead or lag behind other sections of the same wavefront. This produces the undesirable condition of an uneven wavefront.[6]

In other words, these random temperature fluctuations in different regions of the atmosphere produce a non-uniform and constant swirling mixture of air, which degrades the quality and intensity of a light beam as it moves unpredictably through each sector of the atmosphere. Instead of all parts of the light wavefront traveling in a straight flat line in the same direction, atmospheric turbulence causes the light to follow an erratic path. It is this phenomenon that causes stars to "twinkle." The goal of adaptive optics is to align all sections of the wavefront to move in the same direction and replace the twinkle with a sharp image.[7]

Adaptive optics offered one potential solution by restoring light almost to its original, undisturbed condition outside the atmosphere. Overall, the term *adaptive optics* refers to an optical system that can adapt by compensating for atmospheric distortions induced in light waves. As one expert put it, "It's a method of automatically keeping the light focused when it gets out of focus."[8]

Fugate and his team first attacked the atmospheric turbulence problem by demonstrating a Rayleigh laser guide star in 1983 at a remote optical site at Kirtland *(Figure 4)*. The laser guide star concept relied on a principle of physics called Rayleigh scattering—named after Lord Rayleigh, winner of the Nobel Prize in Physics in 1903—whereby focused laser light is reflected in all directions by molecules (nitrogen, oxygen, and aerosols) in the atmosphere. (Shining a searchlight in the sky at night, with the reflecting light dispersing in all directions, is similar to Rayleigh scattering.) Researchers speculated that if a telescope and an outgoing laser were both pointed towards a prominent object in the sky—such as a star—the Rayleigh-reflected laser light and the starlight would

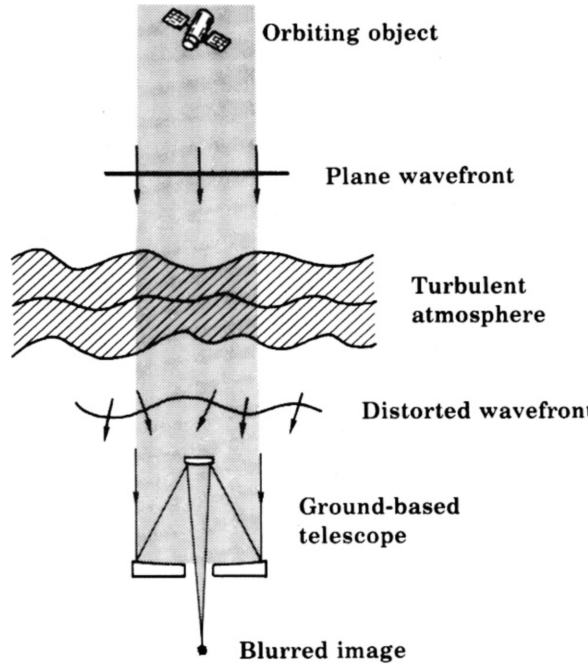

Figure 3. Anatomy of a blurred image

travel downward along a near-identical return path in the atmosphere to the telescope on the ground and encounter nearly identical turbulence.[9]

But why did scientists need light from both a star and a Rayleigh laser guide star? Only a tiny percentage of stars are bright enough to deliver enough light to a telescope to determine the amount of distortion across the light's wavefront. That was the main reason scientists began investigating artificial Rayleigh guide stars. The wavefront sensor in an adaptive optics system "consumes" most of the light from a dim star, leaving insufficient starlight to be sent to a camera to image the star. A Rayleigh laser guide star provides additional light to send to the wavefront sensor, enabling the starlight to bypass the measuring device and travel directly to a deformable mirror, and from there to enter a camera and produce a clear image. So, the main advantage of a laser beacon is that it is an artificial bright light source that is independent of the light from the observed object and, therefore, allows all the light from the viewed object to be used by a camera doing the imaging.[10]

Important as it was, the Rayleigh guide star experiment was strictly an attempt at "measurement." As one scientist described it, the guide star experiment was like taking a picture or x-ray of the atmosphere. The question was whether the backscatter from a Rayleigh guide star could be used to measure the extent of distortion (phase errors) induced on the laser wavefront.[11]

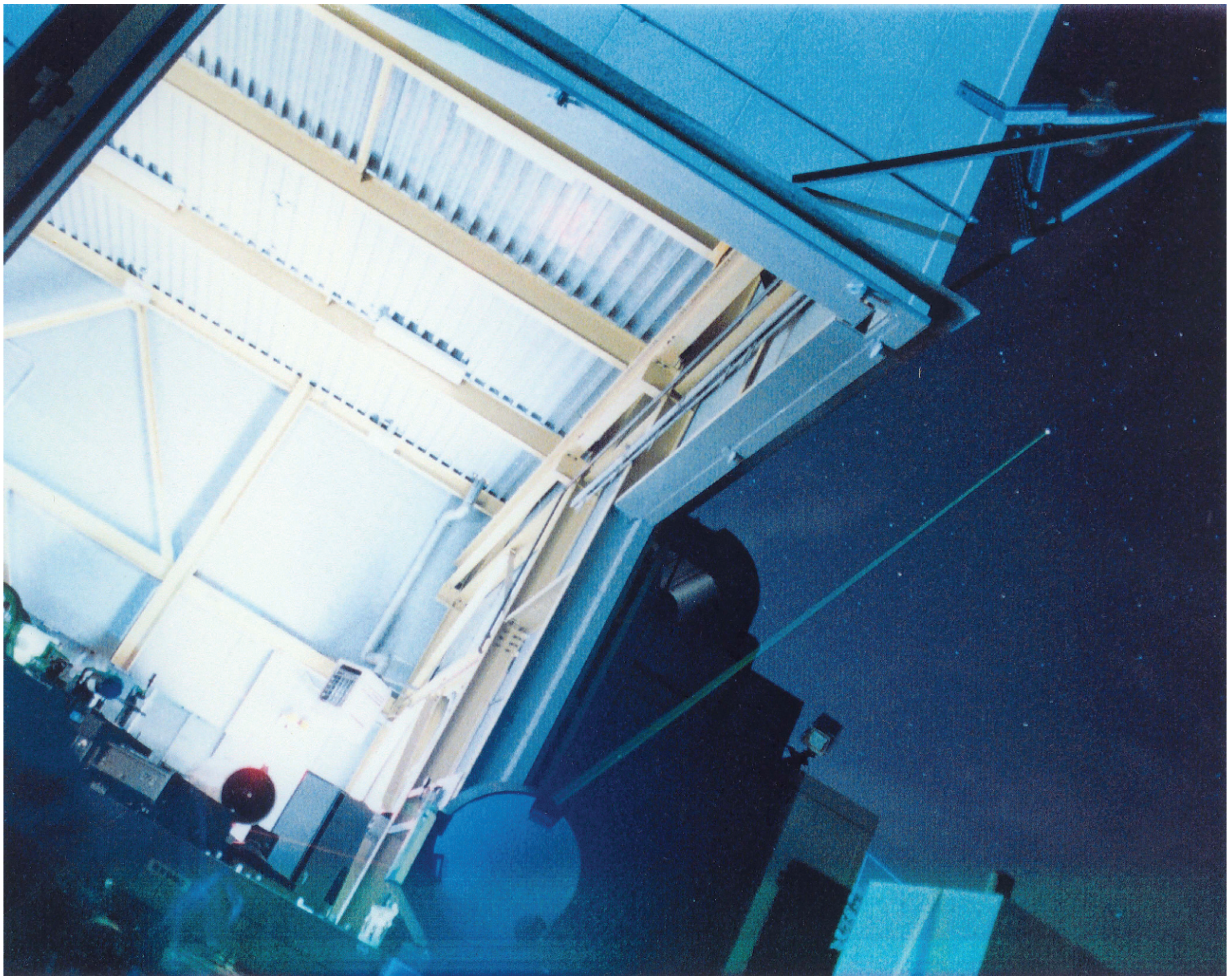

Figure 4. Rayleigh laser guide star experiment (1983) with laser pointing to the star Polaris.

To confirm that the air turbulence measurements were of the highest quality, Fugate's team compared the Rayleigh experimental data to an independent standard of measurement—the "truth" reference—to show the Rayleigh numbers were correct. Light from a star was the controlled variable or standard of comparison. So experimenters pointed their narrow laser beam to within a few microradians of the star Polaris, the famed North Star *(Figure 4)*. Polaris was chosen because it was one of the rare "bright" stars that could supply an adequate amount of light. The starlight and the laser backscatter light would travel through nearly identical paths from the atmosphere to a telescope, in this case the 1.5-meter telescope at Starfire Optical Range at Kirtland.[12]

Findings showed unequivocally that measurements of distortions in the starlight closely matched those of the guide star scattered light. Fugate's team was pleased by the outcome of the Rayleigh experiment because the data proved the theory of a laser guide star. "These results demonstrate qualitatively," Fugate proudly pronounced, "that laser guide star beacons are effective in measuring atmospheric-turbulence-induced wavefront distortion."[13]

Although Fugate's 1983 experiment was not conducted using an operational adaptive optics system, its success laid the groundwork for development of a closed-loop system. Such a system required a wavefront sensor and a high-speed processor that sent electrical signals to actuators (small pistons) attached to the backside of a deformable mirror. Depending on the strength of the electrical signals, each actuator pushed or pulled to change the shape of the mirror surface. As distorted light struck the irregular mirror surface, the beam was "straightened out" or compensated so a clear image could be formed. It was this kind of closed-loop adaptive optics system that Fugate used in his Generation I experiments to capture the revolutionary compensated images he showed to the astonished crowd of astronomers in Seattle in 1991.[14]

The Rayleigh guide star work marked a milestone in the history of technology that had important consequences. A team of Air Force scientists demonstrated

the application of the laser guide star, a revolutionary breakthrough in the annals of optical research that would be pivotal to the development of future adaptive optics systems. Not only did these experiments bolster the Air Force's situational awareness mission, they resulted in a classic case of technology transfer from the military to the civilian sector. Laser guide stars and the subsequent development of sophisticated adaptive optics systems on ground-based telescopes produced hitherto impossible, high-resolution images that were incredibly beneficial to the world's astronomers. Indeed, many considered adaptive optics to be the most important optical advancement in astronomy since the discovery of the telescope.[15] ❑

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Endnotes

[1]Paper, Robert Q. Fugate, "Experimental Demonstration of Real Time Atmospheric Compensation," May 27, 1991; Phillips Laboratory News Release (91-36), "Astronomy Breakthrough," May 27, 1991; Interviews with Robert Q. Fugate, April 21 and May 14, 2003.

[2]Interview with William E. Thompson, October 9, 2002.

[3]Ibid; Interview with Wayne G. Van Citters, April 14, 2004.

[4]Paper, Fugate, "Experimental Demonstration of Real Time Atmospheric Compensation," May 27, 1991; Interviews with Fugate, April 21 and May 14, 2003.

[5]Interview with Thompson, October 9, 2002; Interview with Van Citters, April 14, 2004.

[6]Tech report (AFRL-DE-PS-TR-1998-1054, Pt. 1), Glenn A. Tyler et al., the Optical Sciences Company, "Adaptive Optics: Theory and Applications," December 1999, pp. 2–8; Paper, Raymond P. Urtz Jr. (RADC), and James W. Justice (DARPA), "Compensated Imaging" June 12, 1975; Robert Q. Fugate, "Laser Beacon Adaptive Optics," *Optics and Photonics News*, June 1993, pp. 14–19.

[7]See note number 6.

[8]Robert K. Tyson, *Principles of Adaptive Optics* (Boston: Academic Press, 1997), p. 3.

[9]R. Q. Fugate, et al., "Measurements of atmospheric wavefront distortion using scattered light from a laser guide-star," *Nature*, September 12, 1991, pp. 144–146; Interview with Fugate December 16, 2002.

[10]See note number 9.

[11]Paper, Fugate, "Experimental Demonstration of Real Time Atmospheric Compensation," May 27, 1991; Interview with Fugate, April 21, 2002; Interview with Thompson, February 11, 2003.

[12]See note number 11; Fugate et al., "Measurement of atmospheric wavefront," September 12, 1991, pp. 144–146; USAF News Release (91-36), "Astronomy Breakthrough," May 27, 1991.

[13]Fugate et al., "Measurement of atmospheric wavefront," September 12, 1991, pp. 144–146; Paper, Fugate, "Experimental Demonstration of Real Time Atmospheric Compensation," May 27, 1991; Interview with Thompson, February 11, 2003; Notes, Fugate to Duffner, subj: Laser guide stars, June 10, 2004.

[14]Interview with Fugate, April 21, 2003; Interview with Thompson, February 11, 2003.

[15]Mount Wilson Observatory, "Adaptive Optics," http//www.mtwilson.edu/ao.